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Assessment of out-of-plane strength of masonry infills through a FE augmented dataset

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Abstract

Evaluation of the out-of-plane strength of infilled frames is a matter of fundamental importance. In fact, by observing post-earthquake damage, it has been noted that infills subject to in-plane and out-of-plane inertial forces may achieve collapse due to out-of-plane actions. This mode of collapse may result quite dangerous to the people in the proximity of a building subjected an earthquake. The possibility to perform an accurate safety assessment is fundamental to prevent this type of failure. Different expressions for evaluating the out-of-plane resistance of infilled frames are available in the literature. These are based on analytical formulations validated on the basis of too limited or too large experimental datasets. This implies that these expressions are often conflicting, showing good reliability in some cases and less in others. In order to overcome this drawback, this paper provides the definition of a hybrid database obtained by merging existing experimental test data with additional ones obtained from numerical simulations by means of a refined FE micro-model. A new data-driven empirical expression for estimating the OOP resistance of infilled frames has been developed based on the hybrid database so developed. The new expression has the advantage of taking into account the aspect ratio of the filled frame, the influence of vertical loads, and the influence of the out-of-plane load application mode. Finally, validation tests are performed against experimental and numerical samples.

Keywords: ABAQUS, empirical, FEM, Masonry, Infilled Frames, Reinforced concrete, Data-driven

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1. Introduction

The evaluation of the out-of-plane resistance (OOP) of infilled frames is an issue of primary importance in the seismic risk assessment of frame structures. In fact, although infills are not primary structural elements, they interact strongly with primary structures becoming more vulnerable to out-of-plane (OOP) forces as a result of in-plane (IP) damage due to inertial forces. OOP failure of infills is very dangerous to the safety of people in the proximity of a building during an earthquake. Therefore, simple and reliable verification methods are needed for engineers to perform capacity / demand safety verifications related to the OOP strength of masonry infills.

Experimental and numerical studies have been carried out in recent years to investigate the behavior of infilled frames subjected to combined in-plane and out-of-plane (IP + OOP) actions (Angel, 1994, Calvi & Bolognini, 2001, Morandi et al., 2011, Sepasdar, 2017, Ricci et al., 2018, Di Trapani et al. 2018, Wang, 2019, De Risi et al., 2019, Di Domenico et al., 2021). These studies converge in stating that following a seismic event, infill panels are weakened due to in-plane actions and combined IP and OOP cracks lead to damage of varying magnitude, which goes from the loss of functionality of the infill to its complete collapse. It should also be noted that infill with moderate-to-low slenderness and well restrained sides can develop significant strength and displacement capacity due to the arching mechanism and two-way bending effect that develops under out-of-plane actions. Several studies addressed specifically out-of-plane resisting mechanism (McDowell et al., 1956, Angel, 1994, Abrams et al., 1996, Flanagan & Bennet, 1999a-b, Hak et al., 2014, Furtado et al., 2016, Sepasdar, 2017, Ricci et al., 2018, Akhoundi et al., 2018, De Risi et al., 2019, Koutas & Boumas, 2019, Nasiri & Liu, 2020), developing different formulations estimating OOP resistance to perform safety checks (McDowell et al., 1956, Angel, 1994, Dawe & Seha, 1989, Bashandi et al., 1995, FEMA 356, 1997, CEN, 2005, Ricci et al., 2017, Liberatore et al., 2020). Although starting from similar theoretical consideration, Liberatore et al., 2020 has demonstrated how results provided by these models are often conflicting, giving the impression that some of them are more reliable in some cases and less in others. Three major aspects influence the difficulty of analytical models to achieve a general validity: a) large heterogeneity of masonry constituting materials and different potential combination with the boundary frames in terms of relative strength, stiffness and aspect ratio; b) limited experimental background (e.g. with respect to in-plane tests); c) different OOP test loading condition (e.g. 4-point OOP tests or airbag uniform pressure tests). Because of these uncertainties, the definition of a generalized relationship, able to provide a good estimation of the OOP resistance of masonry infill is still needed.

Considering the above aspects, this paper aims to create a hybrid database that collects data from real experimental tests and is augmented by additionally simulated numerical tests. The latter are obtained by means of a refined FE model realized in ABAQUS environment that has been calibrated and experimentally validated. Parametric analyses were performed on the FE model to generate additional benchmark numerical tests investigating the effect of varying mechanical, geometric, and loading conditions on the ultimate strength of the OOP. The so defined dataset allowed to derive a new empirical expression that estimates the OOP strength of infilled frames as a function of the geometric and mechanical features of an infilled frame, and also considers the out-of-plane loading mode and the effect of gravity loads on the beam. Finally, a reliability comparison with the models available in the literature is presented.

2. Considerations on literature design models for the evaluation of out-of-plane resistance of masonry infills

For the sake of space a selection of only four literature models is presented. One of the most popular expressions for the estimation of the ultimate OOP load capacity of an infilled frames (F_{OOP}) was proposed by Angel, 1994 and Abrams et al., 1996. Those studies evaluated the out-of-plane resistance of masonry infills as a function of the degree of in plane damage. Results brought a formulation able to take in consideration the effect of frame stiffness and infill slenderness ratio (*h/w*) and the effect of previous in-plane damage, the last obtained considering the displacement achieved after the formation of the first crack in the panel.

In the CEN, 2005 a formulation based on the one-way arching mechanism, is provided, proposing a formula which has inverse proportionality with the square of the infill slenderness ratio.

An adjustment of the prediction models by CEN, 2005 has been provided by Ricci et al., 2017, who corrected the expression with the introduction of empirical coefficients, obtained including in the experimental dataset the tests by Angel, 1994, Flanagan e Bennet, 1999, Calvi and Bolognini, 2001, Hak et al., 2014 and Furtado et al., 2016 .

More recently, Liberatore et al.,2020 provided a further updated considering also the influence of the aspect ratio (*h/l*) on the infill.

Previous studies (e.g. Liberatore et al., 2020) have shown significant scattering of predictive results from these expressions, but two major considerations have to be done. The first is that some of these expression (e.g. Angel et al., 1994) were based on a limited experimental dataset. The second is that is it not realistic thinking that these expressions can be reliable in predicting the OOP resistance even of infills with RC of steel frames and also of confined masonry. Considering single categories would be more proper but, of course, this would reduce the experimental database. The strategy adopted in the following of the paper aims to consider only infills with reinforced concrete frames. A selected number of very complete experimental tests was considered to form the database. The latter is expanded through the definition of a numerical database that is generated based on refined FE model of infilled RC frame, experimentally validated. Details of the model definition are provided in the following section.

3. Refined FE micro-model

The refined FE micro-model was realized with the Simulia Abaqus software platform. Masonry blocks constituting the infill were modeled individually as well as frame and reinforcement elements. Mortar joint between blocks and between blocks and columns were modeled by frictional interface elements. The reference experimental test used for the model definition and calibration is specimen 80_OOP_4E by Ricci et al., 2018. The reference test considers a hollow clay masonry infilled RC frame infill restrained at the four sides having dimensions 2350mm x 1830 mm and thickness 80 mm. The out-of-plane load was applied by imposing an out-of-plane displacement with an actuator equipped with four point-load devices. The concrete strength, brick compressive strength parallel to holes and perpendicular to holes were respectively: f_{cm}=36Mpa, f_{bh}=5Mpa, f_{bv}=2Mpa. The concrete damaged plasticity model was used model the behavior of brittle materials, namely concrete frame members and masonry blocks. The blocks were modeled as solid isotropic brick elements. To take into consideration the orthotropic behavior due to the presence of hollows, a quadratic mean between the two compressive resistance in horizontal and vertical direction of the block was used to define a unique reference conventional resistance value ($\tilde{f}_b$), so that:

$$\tilde{f}_b = \sqrt{f_{bh} \cdot f_{bv}} \tag{1}$$

where f_{bh} is the experimental horizontal compressive resistance of the unit and f_{bv} is the vertical one. The conventional elastic modulus of the blocks was estimated as a function of $\tilde{f}_b$, in analogy of what suggested in CEN, 2005 for masonries, as:

$$\tilde{E}_b = 1000 \cdot \tilde{f}_b \tag{2}$$

The constitutive law used to define the compression behaviour of the block is of the parabolic type with a linear softening branch up to the ultimate strain ε_{cu} (Kent & Park, 1971). The model proposed by Hsu & Mo, 2010 was used to describe the tensile behaviour of the blocks. The elastic and plastic parameters in Tab. 1 are used for the materials definition. As regards the angle of dilatancy for the concrete a value of 37° was assumed as suggested in Simulia, 2013, while for masonry an angle of 10° was adopted as suggested by Van der Pluijm et al., 2000. Plastic parameters regulating the eccentricity (ε), biaxial resistance domain f_{b0}/f_{co}, and viscosity were assumed as suggested in Simulia, 2013.

Table 1. Material properties of concrete and masonry blocks used in ABAQUS

Material	Mass density	Elasticity parameters		Plasticity parameters				
	ton/m^3	Young's modulus (MPa)	Poisson's ratio ν	Dilatation Angle ψ	Eccentricity ε	f_{b0}/f_{co}	K_c	*Viscosity*
Concrete	2.5E-09	32308	0.3	37	0.1	1.16	0.667	0.0003
Masonry bricks	1.10E-09	3160	0.2	10	0.1	1.16	0.667	0.0003

Steel reinforcement was modeled using 1D truss elements whose mechanical response is simulated by a simple elasto-plastic with strain hardening material model. Steel rebars were modeled as embedded elements within the concrete, so that relative sliding between steel bars and concrete could not occur. Mortar joints behavior was modeled using elasto-plastic interfaces with friction and cohesion.

All the model elements were modeled by solid 3D elements with 8 nodes (C3D8R) with a sufficiently refined mesh. Fig. 1 shows the scheme of the model assembly (Fig. 1a) and the mesh of the elements (Fig. 1b). A non-linear quasi-static analysis was performed to simulate the test. Out-of-plane displacements were imposed at the four loading plates.

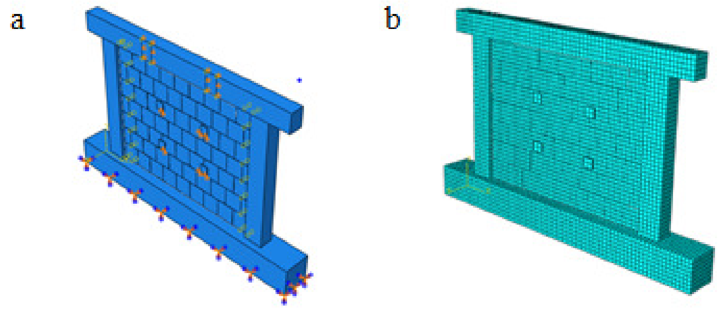

Fig. 1. Definition of the micro-model (a) Scheme of the model assembly; (b) Mesh of the model.

Results of the numerical simulation of the OOP test are shown in Fig. 2 and compared with the experimental response. It can be observed that the model is able to effectively reproduce the experimental behaviour in terms of initial stiffness, peak resistance, and the post peak behaviour.

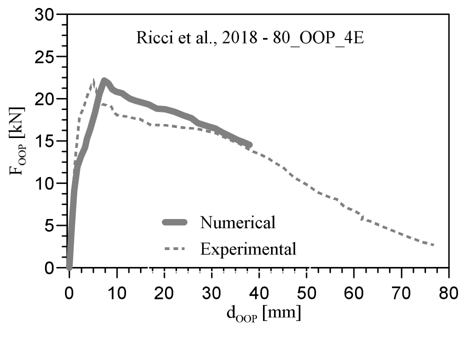

Fig. 2. Comparison between numerical simulation and experimental response of the OOP test 4E by Ricci et al., 2018.

The analysis allowed also an investigation in terms of stress distribution and damage localization. Fig. 3a show the compressive principal stresses on leeward sides of the specimen in correspondence of the peak load. The analysis of the stress field confirms that the model effectively reproduced the horizontal and vertical arching action and the 2-way bending response. The tensile damage pattern resulting by the FE model at the ultimate displacement in also shown in Fig. 3b.

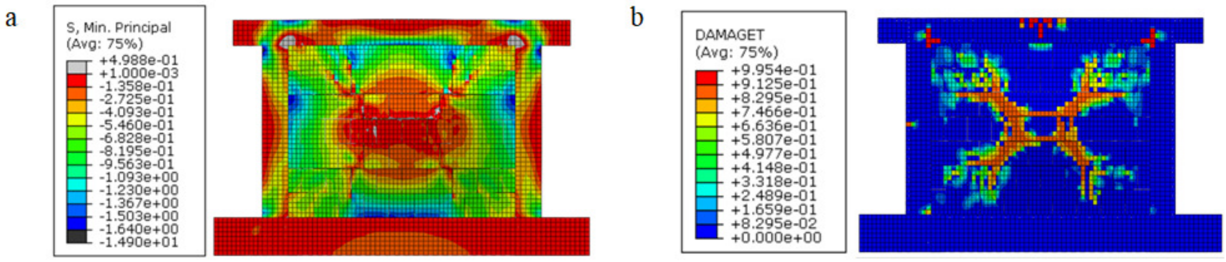

Fig. 3. Leeward side: (a) Compressive stress field at the peak load; (b) Ultimate displacement damage.

After the calibration, the model predictive capacity has been blind-tested against two further experimental tests. These were specimens 120_OOP_4E by Ricci et al., 2018 and De Risi et al., 2019. These two specimens were modeled according to the above described procedure. Experimental / numerical comparisons are shown in Fig. 4. The latter, besides validating the model, confirmed its suitability to be used as a reliable predictive tool to generate reliable simulated tests.

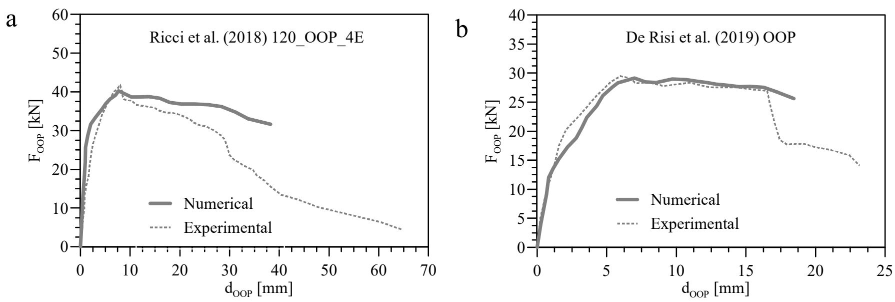

Fig. 4. Comparison of numerical and experimental OOP response: (a) Specimen 120_OOP_4E by Ricci et al., 2018; (b) Specimen by De Risi et al., 2019 OOP.

4. Parametric investigation

The additional FE tests were generated starting from the reference models and individually varying single parameters. In this way, the influence of each variation to the overall resistance was analyzed. Varied parameters were the infill slenderness (*h/t*), the blocks conventional resistance ($\tilde{f}_b$), the entity of the distributed load applied on the upper beam (q).

The variation of the slenderness ratio was performed on two different models, characterized by a different aspect ratio (*w/h*=1-1.28). The slenderness was varied between 9.15 and 22.87, to cover a sufficiently wide range. Results confirmed inverse proportionality between OOP ultimate load and slenderness (Fig. 5).

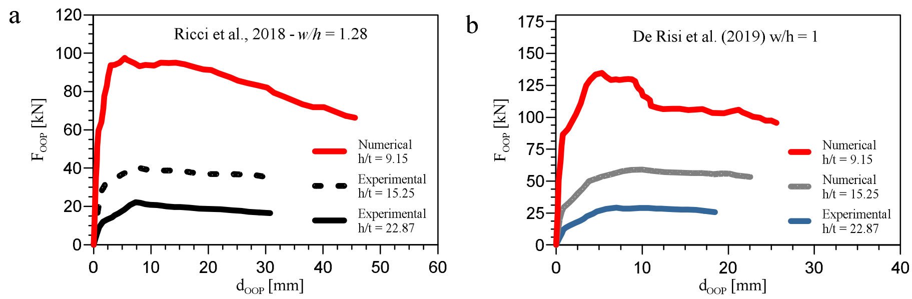

Fig. 5. Effect of slenderness variation: (a) Reference specimen by Ricci et al., 2018 (*w/h*=1.28); (b) Reference specimen in De Risi et al., 2019 (*w/h*=1).

The effect of units resistance variation was evaluated on three different models, Ricci et al., 2018 (infill thickness 80 and 120 mm) and De Risi et al., 2019. The latter was varied in the range 0.5-2.0 $\tilde{f}_{b,ref}$, where $\tilde{f}_{b,ref}$ is the conventional resistance originally used in the calibration and validation phases. Results show that an increment of the unit strength involves an increase of the out-of-plane resistance of the infilled frame (Fig. 6). This behaviour seems to be characterized by a limit, beyond which further increases of the unit strength do significantly affect the OOP resistance.

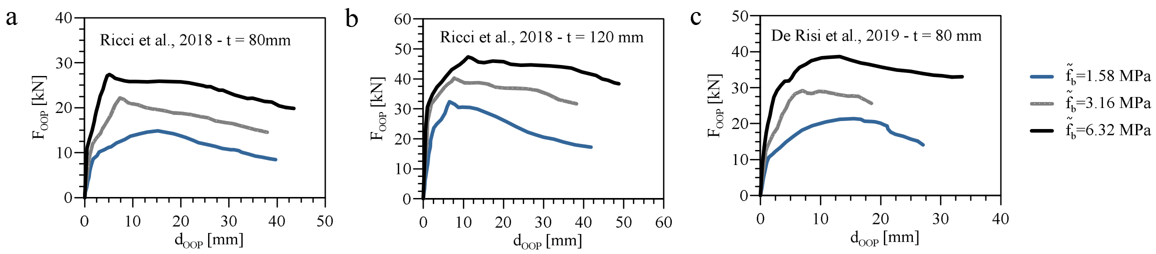

Fig. 6. Effect of unit's compressive strength on the ultimate OOP capacity: (a) Reference specimen by Ricci et al., 2018 (*t*=80 mm); (b) Reference specimen in Ricci et al., 2018(*t*=120 mm); (c) Reference specimen in De Risi et al., 2019 (*t*=80 mm).

The influence of a distributed load acting on the top beam was finally investigated using specimen 80_OOP_4E as reference. The load was varied in the range 0-30 kN/m.

A linear increment of the OOP resistance was observed as a function of the extent of the vertical load (Fig. 7). This trend is justified by the pre-stressing action exerted on the infill by the compression load, which makes the arching mechanism more effective.

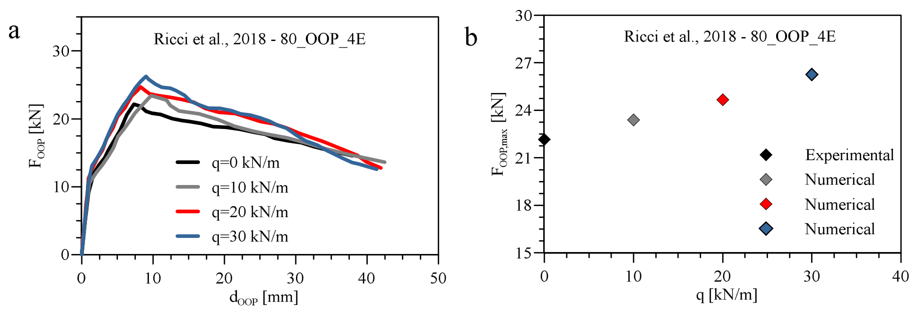

Fig. 7. Effect of vertical load (q) on the ultimate OOP capacity. a) OOP force-displacement curves; b) Maximum OOP force vs. *q*. Reference specimen in Ricci et al., 2018 (*t*=80 mm).

5. Definition of the empirical formulation

An hybrid database composed of 9 experimental tests (Angel, 1994, Calvi & Bolognini, 2001, Sepasdar, 2017, Ricci et al., 2018, Akhoundi et al., 2018, De Risi et al., 2019, Koutas & Bournas, 2019, Nasiri & Liu, 2020) and the 13 numerical simulations presented before was assembled to put in relation test results with the geometric and mechanical properties of the infilled frames. Data processing was performed to derive an empirical analytical relationship between the out-of-plane resistance the most relevant geometric and mechanical features of a generic infilled RC frame. The reference experimental tests and the numerical simulations are collected in Tab. 2 together with the specification of the parameters varied for each test/simulation and the modality of application of the vertical load. This latter parameter has been specifically investigated to evaluate its influence in conditioning the out-of-plane resistance. To highlight this aspect a specific test was carried out using the reference FE model 8_OOP_4E (Ricci et al., 2018) and simulating its OOP response by applying a uniform load (instead of the original 4-point loading), which is more similar to the actual trend of inertial forces. Results evidenced a double OOP resistance if the infill is uniformly loaded (Fig. 8).

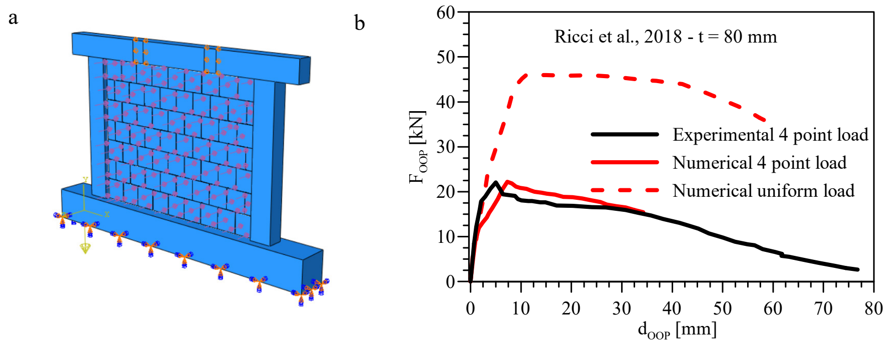

Fig. 8. Effect of the way of application of the OOP load on the ultimate capacity: a) Simulation of the application of the uniform load on the FE model; b) OOP response of the FE model with 4-point and uniform load.

In consideration of results of previous numerical tests and past experimental evidence the search for a new empirical formulation considered the following major parameters: aspect ratio of the infill (*w/h*), slenderness of the infill (*h/t*), conventional resistance of the units ($\tilde{f}_b$), resulting vertical load acting on the upper beam ($Q = q \cdot w$) and mode of application of the OOP load (α). The latter coefficient allows uniformizing OOP test results obtained by 4-point load tests and airbag tests (uniform loading). The proposed predictive relationships allows direct evaluation of the undamaged OOP resistance of an infilled frame. The latter has the following expression:

$$F_{OOP} = \alpha \cdot \left[\left(\frac{w \cdot h}{100} \right)^{\beta} \left(\frac{w}{h} \right)^{-0.41} \tilde{f}_b^{0.43} \left(\frac{h}{t} \right)^{-1.67} + 0.058 \cdot Q \right] \quad (3)$$

where β is an aspect-ratio related coefficient defined as:

$$\beta = -0.372 \cdot \left(\frac{w}{h} \right)^2 + 0.787 \frac{w}{h} + 0.3455 \quad (4)$$

and α is the conversion factor used to make experimental 4-point load test and uniform load tests comparable and assuming the following values:

$$\begin{cases} \alpha = 1 & 4-\text{point load} \\ \alpha = 1.557\left(\dfrac{w}{h}\right)^{1.138} & \text{uniform load} \end{cases} \qquad (5)$$

A comparison between experimental and numerical OOP resistance values with the predictions by Eq. (3) is shown in Fig. 9, demonstrating very low dispersion of results by the proposed empirical model.

Table 2. Hybrid experimental-numerical database

Test reference	Specimen	h (mm)	w (-)	w/h (mm)	t (mm)	h/t (-)	$\tilde{f}_b$ (N/mm²)	Q (kN)	Load appl.	F_{OOP} (kN)
Ricci et al., 2018	80_OOP_4E	1830	2350	1.28	80	22.9	3.16	0	4-point	22.16
	120_OOP_4E	1830	2350	1.28	120	15.3	3.16	0	4-point	41.90
De Risi et al., 2019	OOP	1830	1830	1.00	80	22.9	4.74	0	4-point	29.14
Calvi & Bolognini, 2001	10	2750	4200	1.53	135	20.4	6.57	0	4-point	33.70
Koutas & Bournas, 2019	S_CON	1250	1700	1.36	65	19.2	21.00	0	4-point	29.00
Angel, 1994	1	1625	2438	1.50	48	33.9	23.90	0	Airbag	33.90
Sepasdar, 2017	IF-ND	980	1350	1.38	90	10.9	12.80	0	Airbag	87.71
Akhoundi et al., 2018	SIF-B	1635	2415	1.48	80	20.4	4.29	0	Airbag	39.70
Nasiri & Liu, 2020	IFNG	980	1350	1.38	90	10.9	25.00	0	Airbag	140.00
FEM – Analyses	FEM-R-L1	1830	2350	1.28	80	22.9	3.16	0	Airbag	45.43
	FEM-DR-G1	1830	1830	1.00	120	15.3	4.74	0	4-point	56.98
	FEM-R-G2	1830	2350	1.28	200	9.2	3.16	0	4-point	101.39
	FEM-DR-G2	1830	1830	1.00	200	9.2	4.74	0	4-point	133.72
	FEM-R-M1	1830	2350	1.28	80	22.9	1.58	0	4-point	16.29
	FEM-R-M2	1830	2350	1.28	80	22.9	6.32	0	4-point	29.57
	FEM-DR-M1	1830	1830	1.00	80	22.9	2.37	0	4-point	21.49
	FEM-DR-M2	1830	1830	1.00	80	22.9	9.48	0	4-point	39.00
	FEM-R-M3	1830	2350	1.28	120	15.3	1.58	0	4-point	32.07
	FEM-R-M4	1830	2350	1.28	120	15.3	6.32	0	4-point	58.20
	FEM-R-Q1	1830	2350	1.28	80	22.9	3.16	23.5	4-point	23.31
	FEM-R-Q2	1830	2350	1.28	80	22.9	3.16	47.0	4-point	24.68
	FEM-R-Q3	1830	2350	1.28	80	22.9	3.16	70.5	4-point	26.04

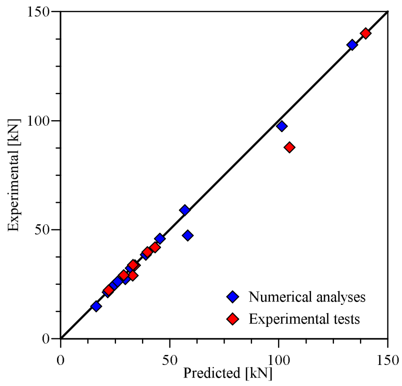

Fig. 9. Comparison between experimental and predicted OOP resistance values by the proposed formulation.

6. Comparisons with the existing predictive models

A comparative analysis of the proposed relationship with respect to the predictive models available in the literature is finally carried. For this comparison only experimental test results were considered. The reference experimental tests and the respective experimental and predicted OOP resistance values are shown Tab. 3. It can be observed how the proposed model is able to fit better than the other predictive models. The models proposed by Ricci et al., 2017 and Liberatore et al., 2020 provided also an adequate reliability although they seem having an overestimation tendency. On the contrary, the model by Angel, 1994 significantly underestimated the experimental results. The improved predictive capacity shown by the proposed model with respect to the previous ones is justified by the fact that this model enriches the formulation taking into account additional information such as the influence of vertical loads and the mode of application of the out-of-plane load. Moreover, the model is specifically calibrated using only OOP tests of infilled RC frames, therefore it results more accurate than the other formulations base on a more heterogeneous database.

Table 3. Experimental OOP resistance values and their analytical prediction.

Experimental study	Specimen	$F_{OOP,exp}$ [kN]	$F_{OOP,pred}$ [kN] Angel, 1994	EC6 2005	Ricci et al. 2017	Liberatore et al.,2020	**Proposed model**
Ricci et al., 2018	80_OOP_4E	22.16	6.84	14.88	31.10	52.58	**21.95**
	120_OOP_4E	41.90	19.81	30.51	57.37	31.61	**43.20**
De Risi et al., 2019	OOP	29.14	7.13	15.17	26.62	47.88	**28.95**
Calvi & Bolognini, 2001	10	33.70	21.79	30.62	48.30	82.71	**33.99**
Koutas & Bournas, 2019	S_CON	29.00	20.95	55.74	61.44	40.28	**33.03**
Angel, 1994	1	33.90	10.32	39.12	34.07	16.99	**33.15**
Sepasdar, 2017	IF-ND	87.71	47.40	104.89	130.44	170.46	**104.88**
Akhoundi et al., 2018	SIF-B	39.70	3.20	9.45	32.39	80.52	**39.80**
Nasiri & Liu, 2020	IFNG	140.00	91.42	190.80	160.83	99.48	**139.87**
		Mean (exp./pred.)	3.49	1.45	0.83	0.86	**0.97**
		Std. Dev.(exp./pred.)	3.47	1.12	0.24	0.58	**0.07**

7. Conclusions

Assessment of out-of-plane capacity of infilled frames is not straightforward. Available literature models for the prediction of the out-of-plane resistance are often conflicting, being in general too conservative or, on the contrary, overestimating the capacity. The reasons of this inconsistencies are different. First of all, some of the available models (e.g. Angel 1994) are calibrated based on a limited investigation. Conversely, other literature models have been defined using a too wide dataset, including also steel infilled frames or confined masonries. Finally, the way of application of the OOP load influences on the OOP capacity, therefore some formulations can result unsuitable in match experimental results of specimens loaded with different modalities (e.g. 4-point load or uniform load). In consideration of this, a hybrid database, composed of 9 experimental tests and 13 numerical simulations by a refined FE micro-model was specifically defined. FE models allowed increasing the extent of the dataset and to investigate on the influence of some parameters not taken into account by previous experimental investigations (e.g. the influence of distributed load on the upper beams or the influence of the modality of application of the OOP load).

Post-processing of the collected data allowed defining a new empirical relationship for the direct estimation of the OOP resistance of a generic infilled frame. The proposed model showed matching better than the others the experimental results. The reasons of its better capability in estimating experimental results is justified by the following major considerations:

- The model takes into account the way of application of the OOP load, which greatly influences the OOP resistance.
- The model considers the influence of vertical loads which increase the effectiveness of the arching mechanism.
- The model proposes the use of the conventional unit compressive strength ($\tilde{f}_b$) instead of the vertical strength of the masonry as parameter having major correlation with the OOP resistance of the infill.

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